Review of global Higgs coupling fits

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Outline

- Introduction: what we learn from Higgs couplings

- Coupling extraction strategy from LHC experiments

- Future issues as precisions improve

Higgs couplings in the Standard Model

SM Higgs couplings to SM particles are fixed by the mass-generation mechanism.

W and Z: $g_Z \equiv \sqrt{g^2 + g'^2}$, $v = 246$ GeV

$$\mathcal{L} = |\mathcal{D}_\mu H|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$
$$M_W^2 = g^2 v^2/4 \qquad hWW:\; i(g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ:\; i(g_Z^2 v/2) g^{\mu\nu}$$

Fermions:

$$\mathcal{L} = -y_f \bar{f}_R H^\dagger Q_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$
$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f:\; i m_f/v$$

Gluon pairs and photon pairs:
induced at 1-loop by fermions, W-boson.

Higgs couplings beyond the Standard Model

tree level!

W and Z:

- EWSB can come from more than one Higgs doublet, which then mix to give h mass eigenstate. $v \equiv \sqrt{v_1^2 + v_2^2}$, $\phi_v = \frac{v_1}{v} h_1 + \frac{v_2}{v} h_2$

$$\mathcal{L} = |\mathcal{D}_\mu H_1|^2 + |\mathcal{D}_\mu H_2|^2$$
$$M_W^2 = g^2 v^2/4 \qquad hWW: \; i\langle h|\phi_v\rangle (g^2 v/2) g^{\mu\nu} \equiv i\kappa_W (g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ: \; i\langle h|\phi_v\rangle (g_Z^2 v/2) g^{\mu\nu} \equiv i\kappa_Z (g^2 v/2) g^{\mu\nu}$$

Note $\kappa_W = \kappa_Z$. Also, $\kappa_{W,Z} = 1$ when $h = \phi_v$: "decoupling limit".

- Part of EWSB from larger representation of SU(2). $Q = T^3 + Y/2$

$$\mathcal{L} \supset |\mathcal{D}_\mu \Phi|^2 \;\rightarrow\; (g^2/4)[2T(T+1) - Y^2/2](\phi + v)^2 W^+ W^- + (g_Z^2/8) Y^2 (\phi + v)^2 ZZ$$

Can get $\kappa_W \neq \kappa_Z$ and/or $\kappa_{W,Z} > 1$ after mixing to form h.

Tightly constrained by ρ parameter, $\rho \equiv M_W^2 / M_Z^2 \cos^2\theta_W = 1$ in SM.

Higgs couplings beyond the Standard Model

tree level!

Fermions:

Masses of different fermions can come from different Higgs doublets, which then mix to give h mass eigenstate:

$$\mathcal{L} = -y_f \bar{f}_R \Phi_f^\dagger F_L + \text{(other fermions)} + \text{h.c.}$$

$$m_f = y_f v_f/\sqrt{2} \qquad h\bar{f}f: \; i\langle h|\phi_f\rangle(v/v_f)m_f/v \equiv i\kappa_f m_f/v$$

In general $\kappa_t \neq \kappa_b \neq \kappa_\tau$; e.g. MSSM with large $\tan\beta$ (Δ_b).

Note $\langle h|\phi_f\rangle(v/v_f) = \langle h|\phi_f\rangle/\langle\phi_v|\phi_f\rangle$

$\Rightarrow$ $\kappa_f = 1$ when $h = \phi_v$: "decoupling limit".

Higgs couplings beyond the Standard Model

Gluon pairs and photon pairs:

- κ_t and κ_W change the normalization of top quark and W loops.

- New coloured or charged particles give new loop contributions.
  e.g. top squark, charginos, charged Higgs in MSSM

New particles in the loop can affect $h \leftrightarrow gg$ and $h \to \gamma\gamma$ even if h is otherwise SM-like.

$\Rightarrow$ Can treat κ_g and κ_γ as additional free coupling parameters.

Coupling extraction strategy

Measure event rates at LHC: sensitive to production and decay couplings. Narrow width approximation:

$$\text{Rate}_{ij} = \sigma_i \, \text{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}}$$

Coupling dependence (at leading order):

$$\sigma_i = \kappa_i^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_j = \kappa_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum \kappa_k^2 \Gamma_k^{\text{SM}}$$

Each rate depends on multiple couplings. $\rightarrow$ correlations

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$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \kappa_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}}$$

Each rate depends on multiple couplings. $\rightarrow$ correlations

Non-SM decays could also be present:

- invisible final state (can look for this with dedicated searches)
- "unobserved" final state (e.g., $h \rightarrow$ jets)

Unobserved final states cause a “flat direction” in the fit.

Allow an unobserved decay mode while simultaneously increasing all couplings to SM particles by a factor a:

$$\text{Rate}_{ij} = a^2 \sigma_i^{\text{SM}} \frac{a^2 \Gamma_j^{\text{SM}}}{a^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

Ways to deal with this:

- assume no unobserved decays $\leftarrow$ current approach
  (ok for checking consistency with SM; rather model-dependent)
- assume hWW and hZZ couplings are no larger than in SM
  (valid if only SU(2)-doublets/singlets are present)
- include direct measurement of Higgs width
  (only works for heavier Higgs so that $\Gamma_{\text{tot}} >$ expt. resolution;
  $\Gamma_{\text{tot}}^{\text{SM}} \simeq 4$ MeV for 125 GeV Higgs)

No known model-independent way around this at LHC.

ILC gets around this using decay-mode-independent measurement of $e^+e^- \to Zh$ cross section from recoil-mass method.

Current LHC Higgs coupling extraction strategy

Interim recommendations from LHC Higgs XS WG (arXiv:1209.0040)

Parameterize coupling modifications with scale factors. E.g.,

$$(\sigma \times \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

- κ_g^2 can be related to κ_t and κ_b from top, bottom loops (incl. interference) or can be taken as free parameter (allowing for NP in loops)

- κ_H^2 is modification factor of total width: can be related to all the other scale factors or can include new contribution to width.

Higgs mass: included as a nuisance parameter? [I think yes...]
1 GeV uncertainty in M_h $\Rightarrow$ 5% uncertainty in κ_b/κ_W.

Current LHC Higgs coupling extraction strategy

Benchmark parameterizations used for stability in face of limited available data

a) 1 common scale factor (fit of overall signal strength μ)

b) Scaling of vector boson and fermion couplings (κ_V, κ_f fit)

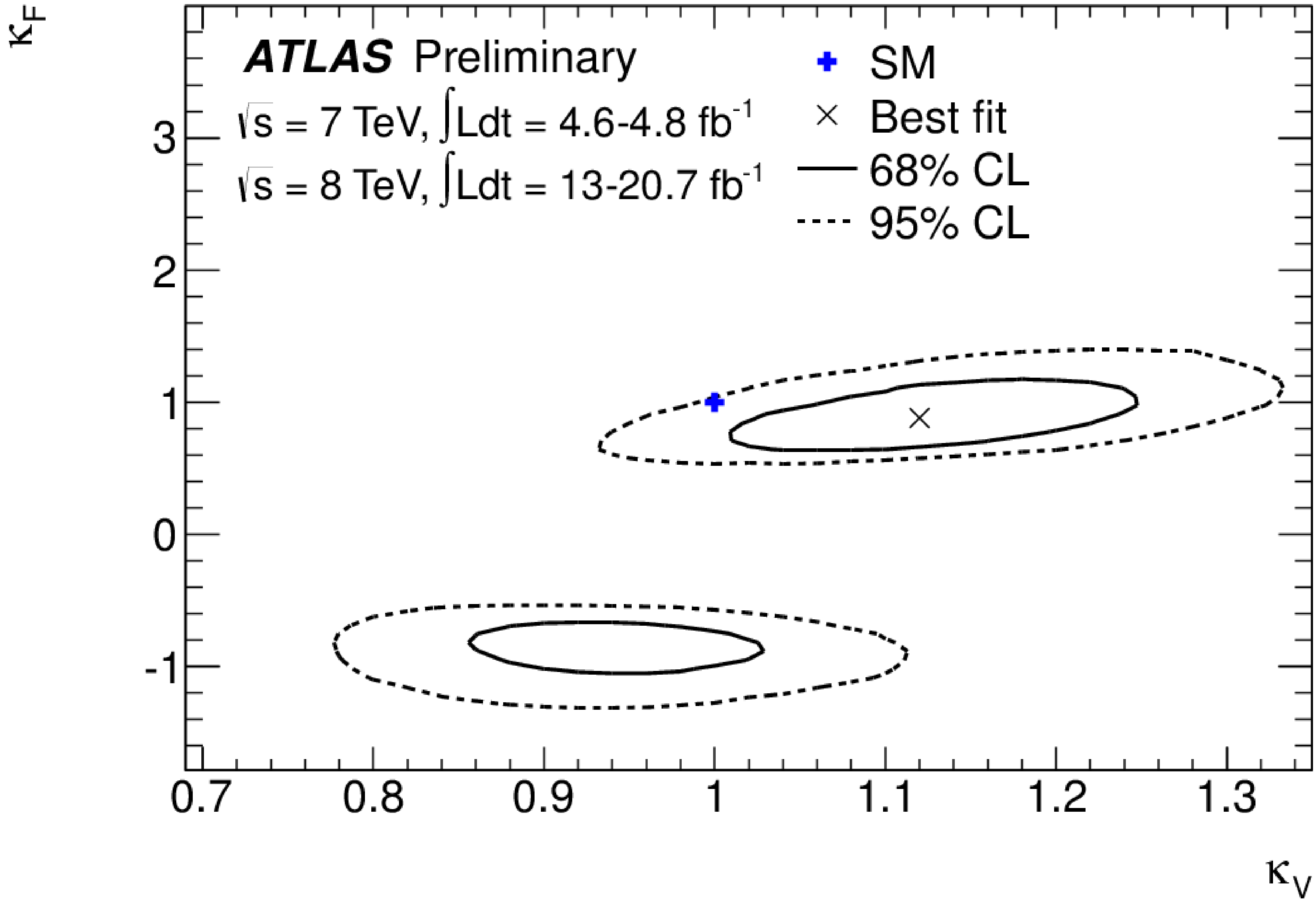
c) Probing custodial symmetry κ_Z, κ_f, $\lambda_{WZ} \equiv \kappa_W/\kappa_Z$

d) Probing the fermion sector

- κ_V, κ_u, $\lambda_{du} \equiv \kappa_d/\kappa_u$
- κ_V, κ_q, $\lambda_{\ell q} \equiv \kappa_\ell/\kappa_q$

e) Probing the loop structure and/or invisible/undetected decays

- κ_g, κ_γ
- κ_g, κ_γ, $\mathrm{BR}_{\mathrm{inv,undet}}$ $\leftarrow ZH$, $H \to$ invis. now directly searched by ATLAS



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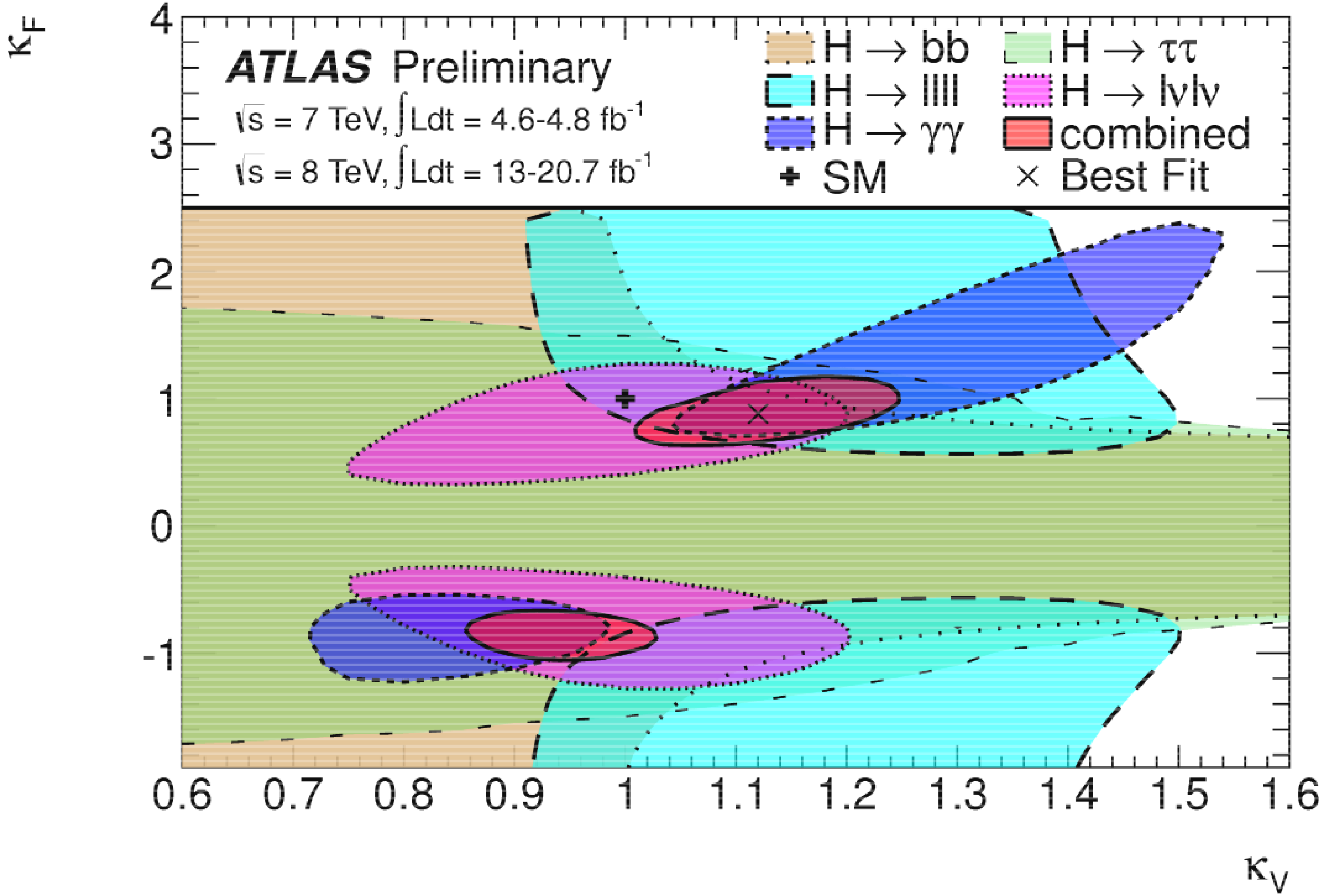

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Future issues 1: QCD uncertainties

Theory uncertainty in Higgs production cross section depends on the kinematic selection.

Theory uncertainty is generally not fully correlated among different kinematic regions of the same process.

E.g.: zero-jet gluon fusion versus gluon fusion selected by VBF selection.

This is being addressed/included by experiments with help from the theorist experts.

Future issues 2: Multiple parameter dependence at higher orders

Higher-order corrections introduce dependence on additional couplings other than the obvious tree-level coupling.

E.g., $\sigma(q\bar{q} \to ZH) \propto \kappa_Z^2$ at tree level but NNLO QCD includes $gg \to ZH$ through a top-quark box diagram: $\propto \kappa_t^2$.

Clear strategy to include these corrections in cross section and BR calculation codes.

Some tools already on the market.

- SusHi: includes production cross sections for 2HDM
- HDECAY v5: includes Higgs coupling scaling factors
- eHDECAY: various EFT parameterizations
- ...

Future issues 3: BSM "electroweak" corrections

Genuine non-SM "electroweak" radiative corrections arise in general in extended models.

E.g., 2HDM has EW RCs involving the additional Higgs states; depend on triple-Higgs couplings between our h and the additional states.

EW vertex corrections depend on p^2 of each of the three external particles: can be different for $H \to ZZ^*$ than for $q\bar{q} \to Z^* \to ZH$ (different p^2 for off-shell Z).

Introduces genuine model dependence beyond what the scaling-factor parameterization can capture.

Not clear whether a model-independent strategy is possible.

Only really becomes an issue once a discrepancy from the SM is observed.

BACKUP SLIDES